Development of Pulsed Plasma Thruster for a Picosatellite

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Abstract: **The University of Malta Astronics research group has been developing a family of low cost PocketQube (PQ) picosatellites, with the smallest having a total mass of under 250 g and dimensions of a 5 cm cube. These satellites will be launched in low meta-stable orbits where an electric propulsion system will be required to maintain the orbit and perform other orbital manoeuvres. The Pulsed Plasma Thruster (PPT) is a promising technology for creating such miniaturised propulsion systems. However, scaling down this technology to fit inside PQs presents new challenges. Hence, different configurations of the coaxial PPT with reliable integrated ignition mechanisms are being developed as part of this project. This paper describes the overall mission feasibility of using PPT technology to reduce a $500\,\mathrm{g}$ 2p PQ's orbit decay at an altitude of $500\,\mathrm{km}$. Two PPT configurations with carbonisation mitigation efforts having a total discharge energy of $0.338\,\mathrm{J}$ per pulse were developed and an analysis of the PPT PQ subsystems is provided. The results include the developed PPT PQ, a simulation of the electric field strength of the two PPT configurations, and the plasma plume generated by the thrusters.**

Nomenclature

A_p	=	Geomagnetic Index
CCFLT	=	Cold Cathode Fluorescent Light Transformer
CWVM	=	Cockcroft Walton Voltage Multiplier
EMI	=	Electromagnetic Interference
EMPPT	=	Electromagnetic Pulsed Plasma Thruster
ETPPT	=	Electrothermal Pulsed Plasma Thruster
F10.7	=	Solar Flux Index
F_{drag}	=	Average Atmospheric Drag Force
LEO	=	Low Earth Orbit
P_o	=	Mechanical Power Required to Maintain PQ Orbit
PCB	=	Printed Circuit Board
PLA	=	Poly-Lactic Acid
PPT	=	Pulsed Plasma Thruster
P_{PPT}	=	Power produced by the Pulsed Plasma Thruster
PQ	=	PocketQube
PTFE	=	Polytetrafluoroethylene

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I.Introduction

Throughout the past five years, the University of Malta Astronics research group has been developing a family of low cost PocketQube (PQ) picosatellites, with the smallest having a total mass of under 250 g and dimensions of a 5 cm cube. These PQ picosatellites can be attached to one another to form larger satellites, each one having complementary subsystems onboard. These PQs are set to navigate in the Low Earth Orbit (LEO) envelope in large constellations , where they will experience very little atmospheric drag, resulting in a slow orbital decay[1].

In the case of system failure, a PQ, which will be travelling at a velocity greater than 7400 m/s will be re-classified as space debris, potentially hindering the operation of future missions, by threatening orbiting spacecraft with possible collisions. In accordance to the Space Debris Mitigation Guidelines, various de-orbiting mechanisms, such as electric propulsion systems, can be used to actively de-orbit and limit the long-term presence of PQs in LEO after the end of their mission[2]. However, it is difficult to guarantee the integrity of such de-orbiting systems at the end of long missions. This is especially true in small low-cost spacecraft.

A better, failsafe methodology is to launch such PQs into a lower meta-stable orbit where they will naturally de-orbit in a relatively short time when malfunctions occur. In this case, electric propulsion systems are required to actively maintain the satellite's orbit while the mission is underway. Besides maintaining the orbit, electric propulsion systems can also be used to perform precise orbital manoeuvres on satellite constellations, arranging the individual constellation members to their respective position for maximum effectiveness.

The Pulsed Plasma Thruster (PPT) is a promising technology for creating such miniaturized propulsion systems[3,4]. However, scaling down this technology to fit inside PQs presents new challenges.[5,6] Hence, different configurations of coaxial PPTs with reliable integrated ignition mechanisms are being developed as part of this project and by other groups.[7,8] The volumetric constraints inside a PQ limit the PPT size to around 2 cm^3 which increases the probability and impact of carbonisation on the surfaces of the solid Polytetrafluoroethylene (PTFE) propellant. This can effectively disable the thrust generating mechanism in a few cycles,[6] and a more resilient configuration needs to be found. A miniaturized high voltage power supply capable of supplying energy to the PPT while adhering to the PQ budget is essential. This must be compact enough to fit inside a PQ, but very carefully designed to avoid stray discharges and other interference with nearby systems.

The objective of this project is to fit the entire PPT subsystem, including power supply, power generation, energy storage, control electronics and thruster into a self-contained 1p module. This module will then be integrated with other PQs, such as the 1p UoMBSaT-1,[9] to create a self propelled 2p PQ system as shown in Fig. 1. Such a system includes a 3-axis attitude determination and control and detumbling will be carried out using motor-driven reaction wheels and copper planar coil magnetorquers,[10] and thrust is achieved using the PPT subsystem.

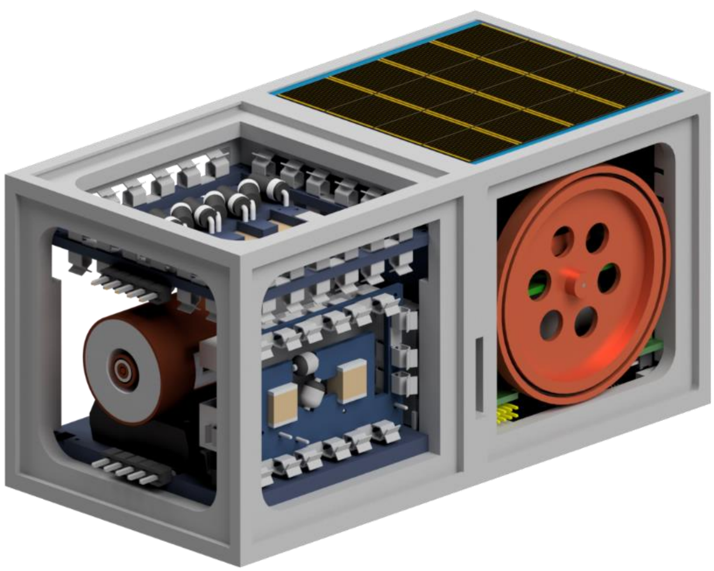


Figure 1. The PPT PQ Integrated with the UMBSAT1 PQ

II. Mission Orbital Requirements

In order to determine the overall mission feasibility of using PPT technology to maintain the PQ's orbit at an altitude of $500\ km$, the parameters in Table. 1 were obtained. At this altitude, the estimated orbital life of a $500\ g$ 2p PQ is 9.7 years assuming a solar index F10.7 of 140, a geomagnetic index A_p of 15 and a worst case orientation with drag cross section of $25\ \mathrm{cm}^2$,[11] which is well within space debris mitigation guidelines.[2] The average air density at this altitude is assumed to be $5.9 \times 10^{-13}\ \mathrm{kg/m^3}$ from Ref. 1. The aerodynamic average drag force F_{drag} experienced by the PQ was calculated using Eq. 1, which is:

$$F_{drag} = \frac{1}{2}\rho v^2 C_D A \quad (1)$$

Where ρ is the density in $\mathrm{kg/m^3}$ of the atmosphere at 500 km, v is the velocity in m/s of the PQ, C_D is the drag coefficient at LEO taken to be 2.2 and A is the surface area in $\mathrm{m^2}$ of the PQ front surface. Hence, the average drag force F_{drag} acting on the satellite at an altitude of 500 km was found to be 8.6×10^{-8} N. The mechanical power P_o in watts required to keep the PQ in orbit was calculated using Eq. 2 below:

$$P_o = \frac{F_{drag} d}{t} \quad (2)$$

Where d is the distance in meters travelled by the PQ and t is the time taken in seconds to travel that distance. Hence, the required mechanical power to maintain the PQ orbit was found to be 0.65 mW. The PPT PQ will have its own power, mass and volume budget, where the average orbit power available from solar panels covering the surface of the PPT module is 300 mW.[9] Four parallel capacitors having a capacitance of 0.47 uF each will be charged to 600 V, producing a total discharge energy of 0.338 J per pulse. As the thruster discharge energy is scaled down, the conversion efficiency from electrical energy to useful kinetic energy also decreases.[4,12] The efficiency of the thruster needs to be large enough such that the useful power produced by the PPT P_{PPT} is larger than the power required to maintain the PQ's orbit. The thruster is set to discharge once every 18 seconds, implying that a minimum target efficiency of electric energy transferred to potential and kinetic energy of 3.9 % is required such that P_{PPT} is greater or equal to P_0 to counteract drag and achieve orbital equilibrium.

Table 1. The Average Environment Parameters and PPT Specifications

Parameter	Value
PQ Altitude	500 km
Average Atmospheric Air Density (ρ) [1]	$5.9 \times 10^{-13}\ \mathrm{kg/m^3}$
Velocity (v)	7619 m/s
Average Atmospheric Drag Force (F_{drag})	8.6×10^{-8} N
Mechanical Power required to Maintain PQ Orbit (P_o)	0.65 mW
Estimate Re-entry of a 2P PQ without PPT [1]	9.7 years
PPT 1P PQ Size Constraint	50 mm × 50 mm × 50 mm
PPT 1P PQ Weight	250 g
Average Orbit Power Available [9]	300 mW
PPT Discharge Energy (E_0)	0.338 J

The PPT could also be used to partially counteract drag to decrease the PQ's orbital decay for missions that do not require a fixed orbit. Operating the PQ at slower orbital decay rate will increase the duration of the mission while reducing the average power consumption of the PPT PQ. Using a similar implementation of the model mentioned in Ref. 1, the orbital decay for a PPT discharging once every 25 seconds over its entire lifetime with a minimum target efficiency of 3.9 % will increase the estimated orbital life of the PQ by approximately 7.8 years, resulting in a total lifetime of 17.5 years. Hence, the PPT should produce enough thrust to decrease the PQ's orbital decay, increasing the lifetime of the picosatellite. The propellant mass required for such a mission is not yet known as measurements regarding the ablated mass per discharge are still ongoing.

III.The Implementation of the PPT Subsystems in a PQ

The electric propulsion system designed for this project is done as a proof of concept to demonstrate that the PPT technology is physically realisable within the volume of a 1P PQ picosatellite without internal electromagnetic compatibility issues.[13] The PPT PQ top level architecture consists of six main blocks as seen in Fig. 2. A 3.7 V lithium-ion battery, which will be charged with solar panels while in orbit supplies power to the electric propulsion circuitry. For laboratory based debugging purposes, a Bluetooth® device is currently utilised for 2 way communications between the PPT which is located inside the vacuum chamber and a computer, acquiring data from the thruster and adjusting the thruster discharge frequency as required. Automatic voltage control is carried out by the onboard microcontroller to adjust the main discharge voltage, allowing the PPT to discharge at different energy levels.

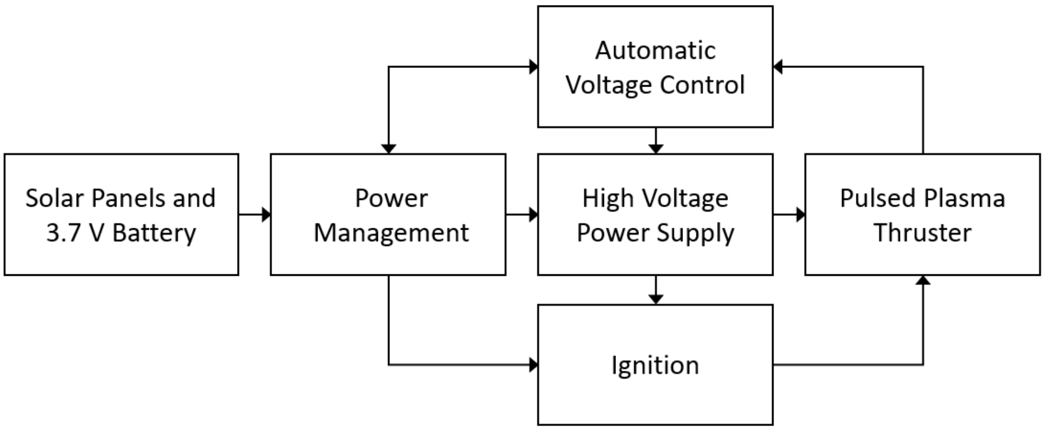


Figure 2. Top Level Architecture of the PPT PQ

A. The Pulsed Plasma Thruster

The miniaturisation of PPT technology presents multiple challenges that have yet to be solved. The volumetric constraints imposed by the PQ standard limit the discharge energy to less than 1 J and the PPT size to around $2\ \mathrm{cm}^3$. The size and discharge energy constraint increases the probability of carbonisation on the solid PTFE propellant surface, disabling the thrust generating mechanism in a few cycles by shorting the PPT electrodes.[6] The size and mass constraints inside the PQ also limit the complexity of the propellant feed mechanisms and the amount of propellant available, leading to a reduction in lifetime and efficiency.[3,14] The Spark plug ignitor, electrode erosion and non-uniform ablation also pose a significant threat to the PPT lifetime.[6,7,14] Furthermore, the electronics are all located in the vicinity of the PPT, making them vulnerable to the Electromagnetic Interference (EMI) produced by each discharge.

However, PPT technology miniaturisation is more achievable compared to other electric propulsion systems.[14] The simplistic design allows for faster and simpler electrode manufacturing, while the solid PTFE propellant removes the need for fuel tanks and valves. The thrust generated by the PPT is mostly produced by electrothermal acceleration rather than electromagnetic acceleration as the discharge energy is below 20 J and the small impulse bit produced by the PPT allow for precise orbital manoeuvres.[3]

In order to mitigate the problem of carbonisation, some research groups suggest increasing the discharge energy per unit surface area of exposed propellant by increasing the capacity of the main discharge capacitors,[6] while others suggest removing the PTFE propellant altogether.[5] Two PPT configurations were developed in this project with the first thruster being an ElectroMagnetic PPT called EMPPT, and the second thruster being an ElectroThermal PPT called ETPPT. These two configurations were selected as to determine the difference in thrust produced by the Lorentz force and the thrust generated by gas dynamics for low energy PPTs.

1. EMPPT

The first coaxial configuration shown in Fig. 3 is designed to accelerate plasma using electromagnetic effects. Structural integrity is achieved co-currently by the PTFE shield insulation (1) and the outer shield electrode (2) which acts as the first line of defence against EMI. The anode electrode (3) of the thruster is made out of copper and is centralised along the thruster. The propellant (4) is a PTFE tube with an exposed surface area of $195.17\ \mathrm{mm}^2$. The

PTFE propellant does not make contact with the anode, drastically reducing the chance of failure due to carbonisation from occurring. The capacitor bank (6) which consists of four 0.47 µF capacitors connected in parallel is located between the anode and the cathode electrodes to reduce the transmission line induction. A slot is located on the PTFE insulator (1) and outer electrode (2) as to connect the capacitor bank to the main discharge power supply. The ignition electrode (7) is held in place by a polyimide tube (8) which is terminated at the middle of the cathode electrode. This reduces the risk of particle deposition on the polyimide surface as the tube is not in the vicinity of the main discharge.

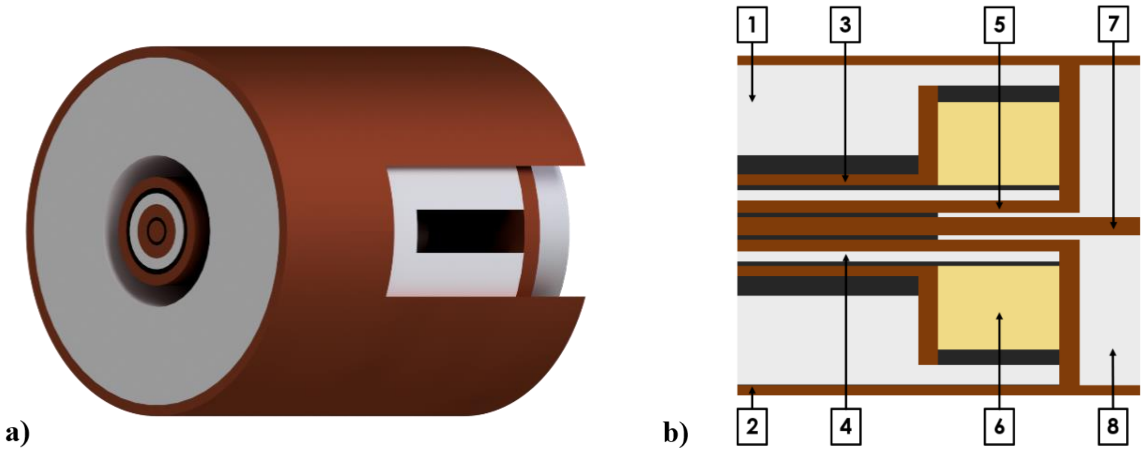


Figure 3. The a) 3D Model and b) Cross-section of the EMPPT *1) PTFE Shield Insulator, 2) Electromagnetic Interference Shield, 3) Anode, 4) PTFE Propellant, 5) Cathode, 6) Capacitor Bank, 7) Ignition Electrode, 8) Ignition Insulation*

2. *ETPPT*

The second configuration which is shown in Fig. 4 makes use of the gas dynamic effect to generate thrust. Similar to the EMPPT, PTFE insulation (1) increases the thruster's structural integrity while the outer electrode (2) attenuates EMI generated by the PPT. The anode (3) is a cylinder copper electrode located at the front of the PPT. The PTFE propellant (4) is a hollow cylindrical tube with an exposed surface area of $43.98\ \mathrm{mm}^2$, which increases with every PPT discharge. The copper anode (5) is located at the back of the PPT and is soldered to the EMI shield. The main capacitor bank (6) in the ETPPT is similar to the one found in the EMPPT, having four 0.47 µF capacitors connecter in parallel. The ignition electrode (7) is held in place by a cylindrical block of PTFE (8). Contact to the ground electrode is only done by the outer edges of the insulator in order to increase the surface area exposed to the main discharge, reducing the probability of carbonisation.

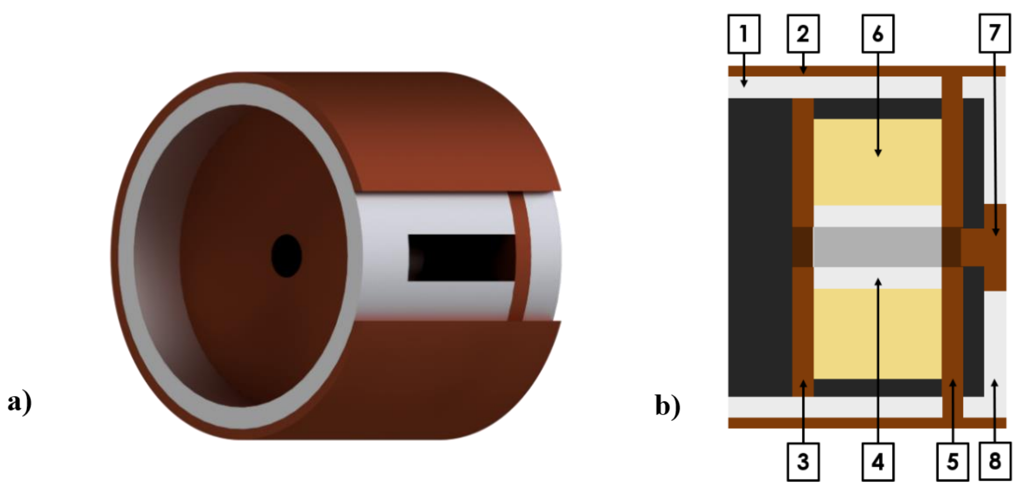


Figure 4. The a) 3D Model and b) Cross-section of the ETPPT *1) PTFE Shield Insulator, 2) Electromagnetic Interference Shield, 3) Anode, 4) PTFE Propellant, 5) Cathode, 6) Capacitor Bank, 7) Ignition Electrode, 8) Ignition Insulation*

B. The Main Discharge Power Supply

The main discharge power supply is capable of charging the capacitor bank inside the PPT to a voltage of $900\ V$. The power supply consists of a Royer Oscillator, a Cold Cathode Fluorescent Light Transformer (CCFLT), and a Cockcroft Walton Voltage Multiplier (CWVM) as shown in Fig. 5, which depicts a simplified circuit diagram of the main discharge power supply.

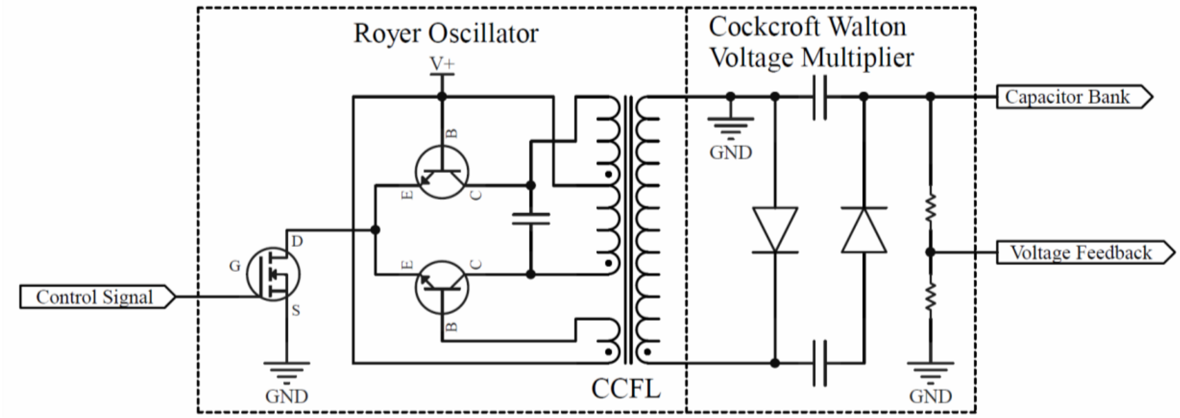


Figure 5. A Simplified Circuit Diagram of the Royer Oscillator, CCFLT, and CWVM

The Royer oscillator, together with the CCFLT makes use of a current driven push-pull topology to generate a $500\ V_{pp}$ sinusoidal wave from the 3.7 V PQ battery. The CWVM which consist of a ladder network made from capacitors and diodes converts the AC voltage from the Royer oscillator into a larger DC voltage. As shown in Fig. 6, Aluminium shields are placed around the high voltage power supply to attenuate the EMI generated by the thruster. Printed Circuit Board (PCB) cut-outs are present to reduce the chance of an unwanted discharge occurring to the aluminium shields due to surface contamination. The PCB cut-outs also remove the need to pot the high voltage components, reducing the overall weight of the PQ picosatellite.

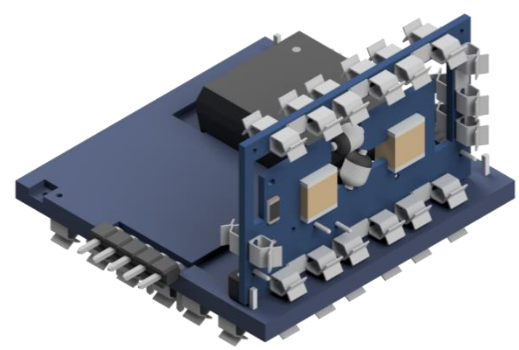


Figure 6. The 3D Model of the Main Discharge

C. The Ignition Subsystem

To successfully initiate the main discharge, a reliable circuit capable of producing a low energy, high voltage pulse for a large number of cycles is essential. Off-the-shelf sparkplugs are too bulky for the PQ standard and their lifetime is insufficient for long term missions. Similar to the main discharge power supply, a Royer oscillator, CCFLT, and CWVM circuit is utilised as shown in Fig. 7. The ignition capacitor ladder consists of eight 15 nF capacitors and eight fast recovery high voltage diodes. The ignition subsystem is capable of charging the capacitor ladder to a maximum voltage of 13.8 kV.

The separation distance between the ground and ignition electrode is set to 0.1 mm for both configurations. To successfully initiate field emissions of electrons from the ignition electrode to the cathode at a pressure of 1×10^{-6} mbar, it was observed from Ref. 15 that the vacuum breakdown voltage at this pressure is approximately 50 kV/mm. This means that for a separation distance of 0.1 mm, a minimum voltage of approximately 5000 V is required to initiate the main discharge.

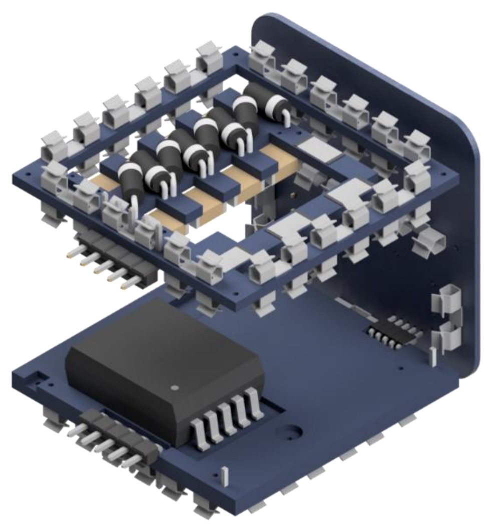
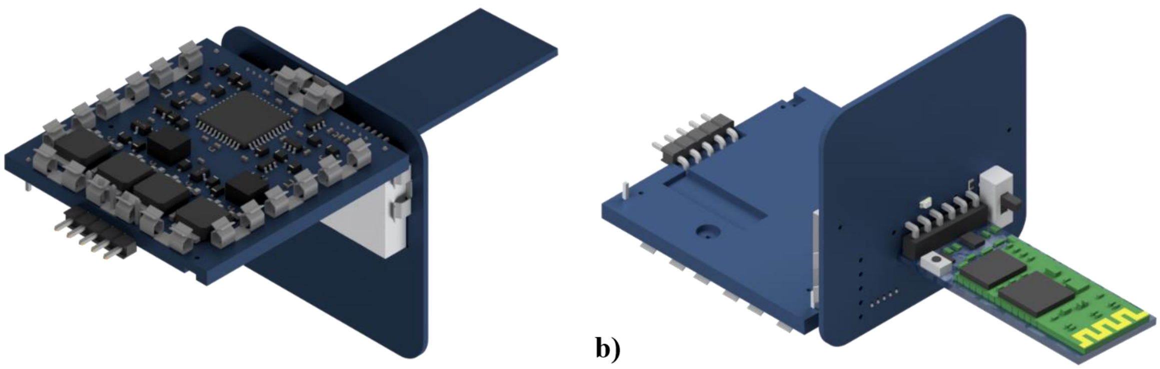


Figure 7. The 3D Model of the Ignition Subsystem

D. The Microcontroller Subsystem

The PPT PQ is controlled by a microcontroller subsystem shown in Fig. 8, operating at 40 MHz. The microcontroller toggles the Royer oscillator according to the voltage present on the main discharge capacitor bank. The analogue to digital convertor integrated within the microcontroller is connected to the main discharge capacitor bank and ignition electrode by means of multiple voltage divider stages. This allows the microcontroller to obtain an accurate measurement of the voltage present on both subsystems. The automatic voltage control allows the PPT to discharge at variable energy levels and at different frequencies. Data of the voltage level on the subsystems are continuously transmitted to the data acquisition system located outside of the vacuum chamber by means of a Bluetooth® device. However, placing an off-the-shelf transmission device without integrated high voltage and EMI protection in the vicinity of the operating thruster caused constant stress on the Bluetooth® module, causing it to fail after a couple of pulses. High voltage and EMI protection is carried out by placing Transient Voltage Suppression diodes and Zener diodes and throughout the subsystem. An aluminium shield covering the subsystem is used to attenuate the EMI generated by the thruster.



a) b)

Figure 8. The Microcontroller Subsystem PCB a) Bottom View, and b) Top View

IV.Results of the PPT Subsystems

The PPT PQ subsystems were soldered and connected as shown in Fig. 9. The Poly-Lactic Acid (PLA) 3D printed frame was removed during tests to avoid outgassing. The PQ was placed inside a vacuum chamber capable of reaching pressures in the 1×10^{-7} mbar range, were the pressure was measured by an Edwards active inverted magnetron (AIM-S-NW25) gauge. The weight of the system excluding the solar panels, batteries, and frame is 88.3 g, which is within the mass constraint of the PQ. Inside the vacuum chamber, the PPT PQ subsystems are powered by two 3.7 V 5000 mAh lithium ion batteries to extend the lifetime of the thruster.

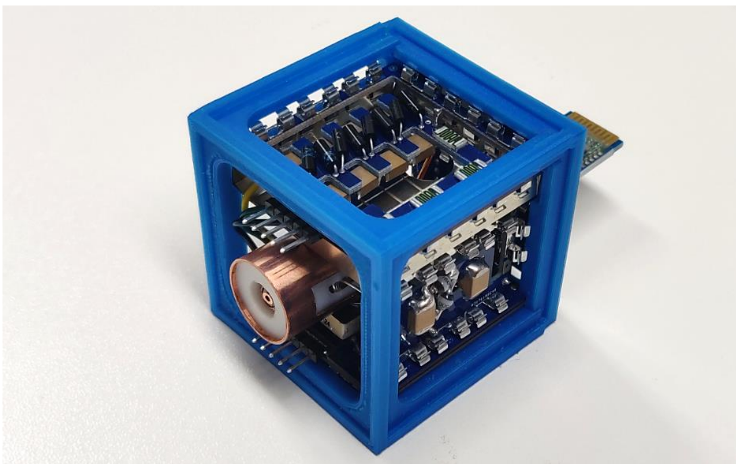


Figure 9. The PPT PQ

A. Power Consumption of the PPT PQ

The power consumption for each subsystem is listed in Table. 2.

Table 2. The Power Consumption of the PPT PQ Subsystems

Subsystem	Power Consumption
Main Discharge Power Supply	2.02 W
Ignition	2.02 W
Microcontroller	0.05 W

The power consumption for the main discharge power supply and ignition subsystems are dependant on the PPT discharge frequency and capacitor charging time. The Bluetooth® power consumption will not be considered since communication will be conducted by the attitude determination PQ while in orbit. As discussed earlier, the PPT should discharge once every 25 seconds to partially counteract the drag and increase the PQ's estimated lifetime by approximately 7.8 years. Additionally, active de-orbiting is also possible once the mission is complete.

The capacitor bank charging time is determined by connecting two voltage probes to the output of the ignition subsystem and the main discharge power supply. The voltage waveform of the ignition and main discharge power supply were plotted in Fig. 10a and Fig. 10b respectively. It was observed that the ignition subsystem took 0.37 s to reach the target breakdown voltage of 5 kV, while charging the main capacitor bank to 600 V took 2.6 s.

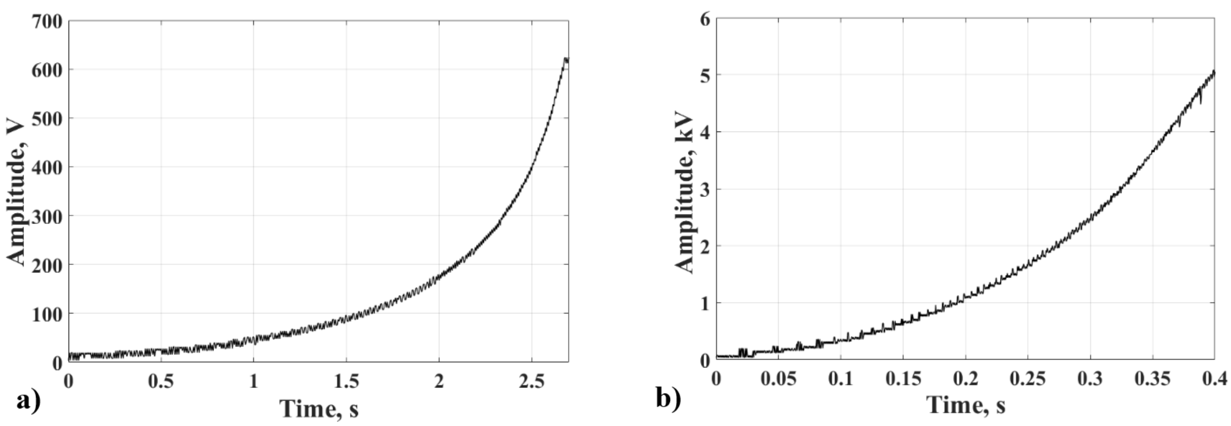


Figure 10. Charging Time of a) The Main Capacitor Bank, and b) The Ignition Subsystem

Taking into consideration the power consumption of each subsystem, the discharge frequency, and the capacitor charging time, the power consumption of the PPT PQ was found to be 291 mW, which is within the average orbit power of 300 mW available. Calculating the efficiency of each subsystem, it was found that the ignition subsystem has a minimum electrical efficiency of 12.5 %, increasing as higher voltages are obtained. The main discharge subsystem electrical efficiency was found to be around 6.4 %. The low efficiency is due to a mismatch in the turns ratio of the CCFLT being used, which will be replaced in future PPT PQ iterations.

B. Electric Field Simulation

A 3D simulation of the electric field strength using CST Studio Suite was carried out for the two thruster configurations. A logarithmic scale of the electric field strength in V/m of the EMPPT and the ET PPT can be seen in Fig. 11 and Fig. 12 respectively. Figure 11a and Figure 12a simulates the electric field prior to ignition, where the main capacitor bank is charged to 600 V and the ignition capacitor bank charged to 5 kV. Figure 11b and Figure 12b simulate the electric field after ignition occurred but prior to the main discharge.

From Fig. 11a and Fig. 12a, the simulation indicates that the electric field strength produced by the ignition electrode will be extremely high during ignition, potentially damaging the electronics that reside behind the thruster. Hence, shielding the ignition electrode wire connection is essential to reduce EMI. The most probable location of the ignition discharge correspond to the points were the electric field strength is the highest from Fig. 11a and Fig. 12a. The simulation results ensure that the PPT ignition electrode configurations for both thrusters where adequately designed. From Fig. 11b and Fig. 12b, the electric field strength of the main capacitor bank was mostly contained within the thruster, implying that the EMI mitigation efforts implemented are protecting the sensitive electronics.

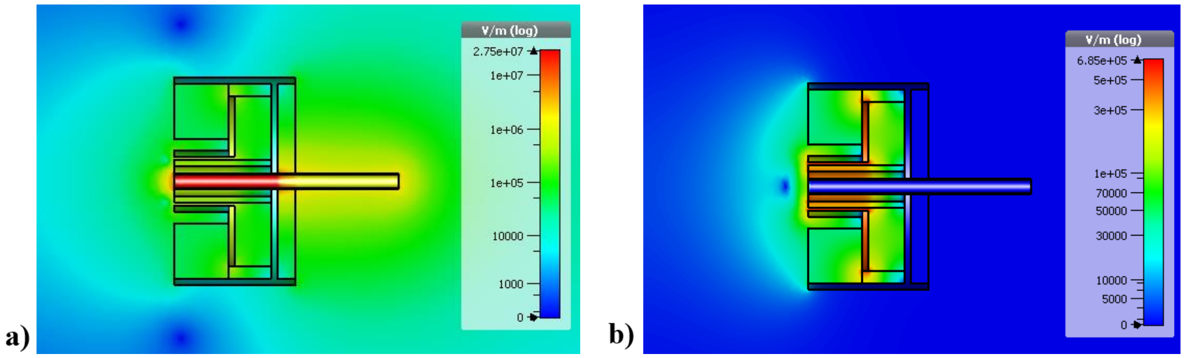


Figure 11. Simulation of the Electric Field Strength of the EMPPT for a) an Ignition of 5 kV and Main Capacitor Bank charged to 600 V and b) Main Capacitor Bank charged to 600 V

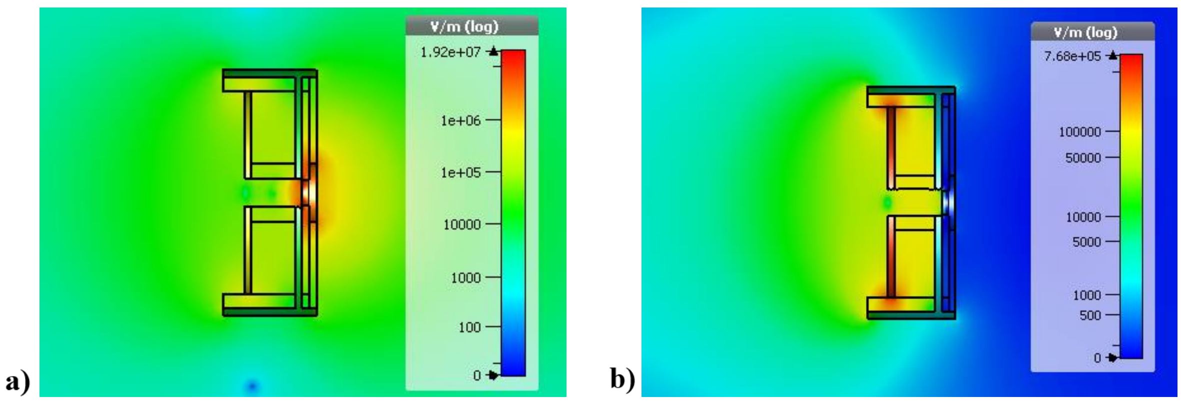


Figure 12. Simulation of the Electric Field Strength of the ETPPT a) an Ignition of 5 kV and Main Capacitor Bank charged to 600 V and b) Main Capacitor Bank charged to 600 V

C. The Main Discharge

The plasma plume generated by the EMPPT and ETPPT at a pressure of 1.2×10^{-5} mbar can be seen in Fig. 13 and Fig. 14 respectively. During this test, the main capacitor bank was charged to 600 V, releasing 0.338 J of energy per pulse. The ETPPT ignition subsystem was placed at the side of the PQ, and the shield electrode was removed to observe the generated plasma. Figure 14 shows the criticality of precise manufacturing and fitting, where the smallest amount of passage allows plasma to leak uncontrollably from the back of the thruster onto the electronic components. The communications module, specifically the Bluetooth® device was damaged due to the plasma and the EMI generated by the discharge. The other subsystems continued to operate without any significant problems due to the EMI mitigation efforts implemented. However, due to the lack of communication with the PQ, the thruster's mass ejected per pulse and lifetime could not be determined.

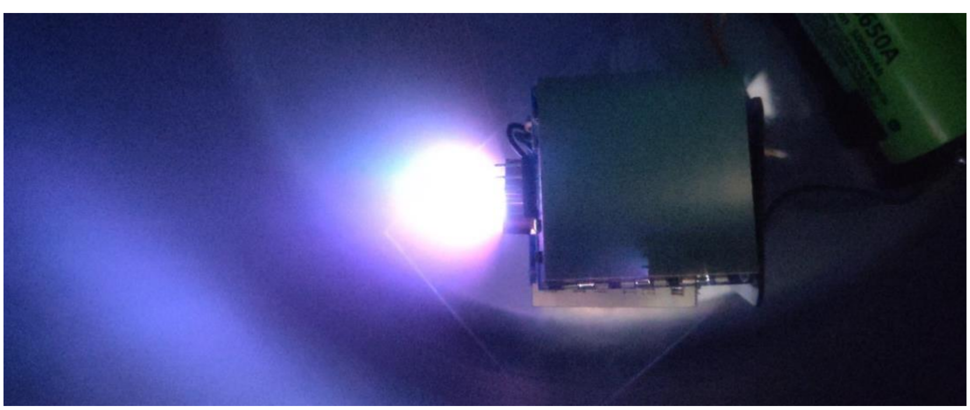


Figure 13. The Plasma Plume of the EMPPT Discharging at 0.338 J

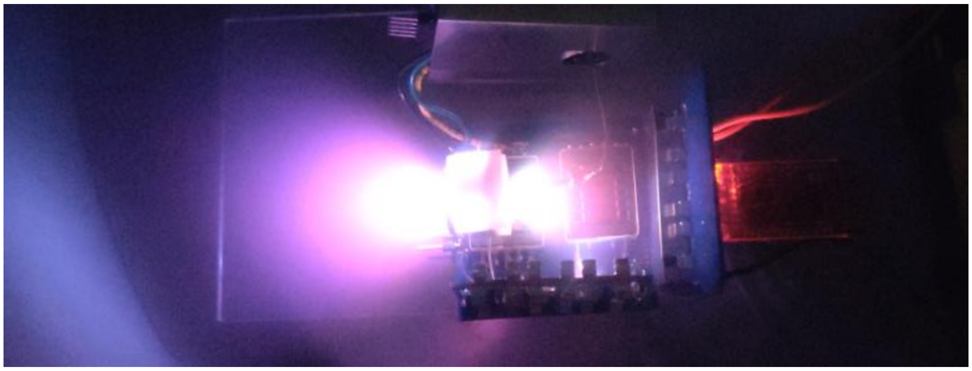


Figure 14. The Plasma Plume of the ETPPT Discharging at 0.338 J

V.Conclusion and Future Work

Launching the PQs into a low meta-stable orbit where they will naturally de-orbit in a relatively short time allows for a failsafe method for decommissioning individual malfunctioning PQs in large constellations. Low cost PPT technology will be required to actively maintain the satellite's orbit while the mission is underway. At an altitude of 500 km with an average air density of 5.9×10^{-13} $\mathrm{kg/m^3}$, the estimated orbital life of a 500 g 2p PQ is estimated to be around 9.7 years. Firing a PPT with a total discharge energy of 0.338 J per pulse once every 25 seconds with a minimum target efficiency of 3.9 % will increase the estimated orbital life of the PQ by approximately 7.8 years.

Two PPT configurations were developed as part of the project, both having a capacitor bank of 1.88 μF. A main discharge supply capable of charging the main capacitor bank to a maximum of 900 V was developed together with an ignition subsystem, capable of producing a high voltage pulse of around 13.8 kV. A microcontroller subsystem was developed to monitor and adjust the voltage on the main capacitor bank, allowing the PPT to discharge at variable energy levels and at different frequencies.

Future iterations of the PPT PQ will include infrared light-emitting diodes instead of a Bluetooth® device for communication to improve reliability, while reducing failure rates. The main discharge power supply circuitry will be re-designed as to increase the subsystem efficiency, and further EMI protection measures will be implemented to ensure the safe operation of the PQ subsystems. In addition to the development of the PPT PQ, the development of a micro thrust measurement system is ongoing. Additional experiments such as the mass ejected per pulse, EMI testing, and, lifetime and reliability testing will be conducted in the near future.

Acknowledgments

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